7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Sensitivity Analysis Using the SWMM LID Control for an Extensive Green Roof in Syracuse, NY

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ABSTRACT
Green roofs are a popular form of sustainable drainage infrastructure. They provide many environmental benefits, such as reducing peak urban stormwater runoff by enabling retention and evapotranspiration similar to natural conditions. Each green roof has unique hydrologic behavior based on physical properties of its growth medium, types of vegetation, structural design, and climate. To improve the application of green roof technology at a site, there is a need to predict stormwater mitigation for several designs before commencing green roof construction. The Storm Water Management Model (SWMM) includes a low impact development control module which makes it possible to model the hydrologic performance of a green roof by directly defining the physical characteristics of its layers. In this study we compare the outputs of the SWMM model with hydrologic performance data from a large extensive green roof in Syracuse, NY from April 2017 to October 2017. Our objectives are to evaluate the performance of SWMM as a long-term modeling software appropriate for predicting the hydrologic performance of a green roof, and to explore changing parameters that might improve hydrologic performance when designing future green roofs. It is expected that this work will help designers of green roofs in climates similar to those of Central NY. In the future, more extensive hydrologic data will be obtained to enable better assessment of SWMM as a tool to help design green roofs.

KEYWORDS
Green roof, SWMM, Green roof modelling, Stormwater management, Green infrastructure

INTRODUCTION
Urbanization contributes to an increase in impervious surfaces and a decrease in land area covered by soil and vegetation. This reduces ecosystem services such as infiltration and evapotranspiration, leading to an increase in urban stormwater runoff. Green infrastructure (GI), which is an important component of low impact development (LID), is being used in urban settings to restore ecosystem services. Green roofs, a form of GI, can restore ecosystem services by retaining and detaining stormwater runoff (Carson et al. 2013; Li and Babcock, 2014) and increasing urban biodiversity (Baumann, 2006; Francis and Lormier, 2011).

Monitoring studies have been conducted to understand the hydrologic performance of green roofs (Peng and Stovin, 2017). Since green roofs vary in configuration, they can range in retention and detention rates (Carson et al. 2013). Though many studies have aided in understanding green roof performance (Heusinger et al. 2018), this indicates the need for engineers to accurately forecast green roof performance through the application of modelling whenever a new green roof is built. The Storm Water Management Model (SWMM) is the most commonly used commercial hydrologic and hydraulic model and provides a quick assessment tool for quantifying the hydrologic performance of GI (Li and Babcock 2014).

The first objective of this study is to assess the SWMM model as a tool for predicting hydrologic performance of a green roof by comparing model outputs with monitoring data from a full-scale, extensive green roof located in Syracuse, NY. The second objective is to perform a sensitivity analysis which will lead to future adjustment of the model parameters and verification. This research is still in an early phase.

METHODS

Green Roof Test Site

The study site is a 5550 sq. meter green roof located on the roof of the Nicholas J. Pirro Convention Center (the OnCenter) in downtown Syracuse, New York (43.04368N, 76.14824W). See Squier-Babcock and Davidson (2018) for a detailed description of the site, drainage design, and monitoring equipment.

Precipitation, runoff, and temperature data have been collected between 4/1/17 and 10/31/17 at 5-minute intervals. Common retention and detention metrics are used to quantify performance. Retention is calculated cumulatively for the entire monitoring period. For the purposes of comparison, rainfall and runoff are expressed as equivalent depth in mm.

EPA SWMM Model

The EPA Storm Water Management Model (SWMM version 5.1.012) is a dynamic hydrology, hydraulic, and water quality simulation model that can be used for both single-event or continuous simulation (Rossman, 2015). The LID controls in SWMM are designed to specifically model GI, such as green roofs. The LID controls work by performing and tracking moisture balances between different vertical layers that are defined by parameters in the graphical user interface.

To model restoration of retention capacity, SWMM has five methods for calculating Potential ET (PET). In this study, following the methods of Peng and Stovin (2017), monthly PET values are calculated using the Hargreaves equation (Marasco et al. 2015) which is standard in SWMM. Note that SWMM models ET strictly as a constant proportion of PET and does not automatically account for the reduction in actual ET (AET) that occurs during moisture limited periods. The proportion can generally be used to account for crop variability or moisture limited months (Peng and Stovin, 2017). For this analysis, the proportion was initially set to 1.

The green roof is modelled in SWMM as a subcatchment that is 100% occupied by the green roof and has an outlet. The dimensions of the subcatchment are 111 m width by 50 m length since the water flow path is perpendicular to the width, which represents the actual flow path of the OnCenter roof. To test the accuracy of the ET component of the model for predicting long-term retention, SWMM is used to generate runoff for the period of 4/1/17 to 10/31/17 at an hourly temporal resolution, avoiding periods of freezing.

The long-term simulation used observed precipitation from the OnCenter green roof site. Monthly PET values were calculated with monthly temperature minimums, maximums, averages, and the geospatial location of the OnCenter. The initial green roof parameter values were estimated from field measurements by Squier and Davidson (2016), Yang and Davidson (2017), and CH2M who performed the initial modelling studies of the OnCenter green roof, and SWMM default values. The values and sources for each parameter utilized in the SWMM Bioretention Module are presented in Table 1.

Table 1. SWMM Parameters and Initial Values for Uncalibrated Simulations

Parameter	Initial Value	Data Source
Subcatchment		
ET coefficient	1	Default
Area	5600 m^2	Squier and Davidson (2016)
Width	110.8 m	Squier and Davidson (2016)
Surface Layer		
Berm Height	0	CH2M Estimate
Vegetation Volume	0	CH2M Estimate
Surface Roughness	0.4	CH2M Estimate
Surface slope	1%	Squier and Davidson (2016)
Soil (substrate)		
Thickness	7.6 cm	Squier and Davidson (2016)
Porosity	0.5	Yang and Davidson (2017)
Field capacity	0.2	CH2M Estimate
Wilting point	0.1	CH2M Estimate
Conductivity	32,400 mm/hr	Yang and Davidson (2017)
Conductivity slope	10	CH2M Estimate
Suction head	41.7 mm	CH2M Estimate
Storage		
Thickness	304.8 mm	CH2M Estimate
Void ratio	0.02	CH2M Estimate
Seepage Rate	0	CH2M Estimate
Clogging Factor	0	CH2M Estimate
Drain		
Flow coefficient	0.075	CH2M Estimate
Flow exponent	0.5	CH2M Estimate
Offset Height	0	CH2M Estimate

Sensitivity Analysis

To determine the parameters that would most effectively minimize the difference between observed and simulated results, a sensitivity analysis was performed using the long-term simulation results. The method suggested by Rosa et al. (2015) and Peng and Stovin (2017) was followed, where each single parameter is adjusted over a range of plus or minus 10 and 50 percent of its original value while holding the other parameter values constant. The difference in annual retention and annual runoff volume were determined for the long-term simulation. Sensitivity was calculated using Eq. (1) (Rosa et al. 2015; Peng and Stovin, 2017):

$$Sensitivity = \left(\frac{\delta R}{\delta P}\right)\left(\frac{P}{R}\right) \quad (1)$$

Where δR = the difference between the original and the new model output; δP = the difference between the original and the adjusted parameter value; R = the original model output; and P = the original value of the parameter.

Validation

The Nash-Sutcliffe model efficiency (NSME) coefficient in Eq. 2 (Nash and Sutcliffe, 1970) was used to reflect the accuracy of the model results as compared to the collected data. An NSME value equal to 1 indicates that the model predicted the performance of the green roof perfectly, while an NSME value greater than 0.5 is still an indication of acceptable model performance (Rosa et al. 2015, Peng and Stovin, 2017). The long-term simulation hourly results were compared in this study to determine an NSME value.

$$NSME = 1 - \left[\frac{\Sigma_1^N \left(Q_m - Q_p\right)^2}{\Sigma_1^N \left(Q_m - Q_{Am}\right)^2}\right] \tag{2}$$

where N = number of samples; Q_m = runoff observed; Q_P = modeled runoff; and Q_{Am} = mean observed runoff.

In the future continuation of this work, single events will be modelled and evaluated with NSME. The subsequent NSME values from this study and future studies will lead to evaluation of the model.

RESULTS

Uncalibrated Long-Term Simulations

Long-term simulations run with these initial parameter values show less than ideal agreement. The cumulative runoff predicted by SWMM totaled 345 mm while the cumulative runoff collected from the green roof totaled 451 mm, or about 100 mm difference. As Figure 1 shows, the model consistently underestimates the amount of runoff compared with the observations. The value of NSME is -0.07. One possible cause of the disagreement is that SWMM may be overestimating ET; work is underway to explore the reasons for the difference. These are the very first results using SWMM with this green roof, and we expect results will improve as we continue to measure roof characteristics rather than using default values and estimates.

Sensitivity Analysis

The results of the sensitivity analysis are presented in Table 2. The negative sensitivity values indicate a decrease in corresponding runoff volume or annual retention, while positive values indicate an increase. The total runoff volume and annual retention were found to be influenced by the ET coefficient, the soil field capacity, and the soil wilting point. The surface slope, soil porosity, soil conductivity, conductivity slope, suction head, storage void ratio, drain flow coefficient, and drain flow exponent were found to have less impact on the model results. For one run, the values were not valid because porosity cannot be smaller than field capacity. Both the annual retention and the total annual runoff were most sensitive to a change in the soil field capacity, followed by the wilting point, and then the ET coefficient. Field capacity influences the retention capacity; wilting point and ET influence retention recovery. Both retention capacity and recovery are essential contributors to annual retention performance. The importance of both ET and field capacity in green roof performance have been cited in many studies (Peng and Stovin, 2017; Cipolla et al. 2016; Stovin et al. 2013).

DISCUSSION

The SWMM bioretention module for a green roof with a drain has the potential to be an accurate model representation. However, the initial results of consistently underestimating runoff points to the way that a green roof's storage capacity is restored – ET. The sensitivity analysis identifies the importance of ET in green roof retention, which is well supported by many studies (Stovin et al. 2013; Peng and Stovin, 2017). The use of the Hargreaves equation, a temperature-based model for ET, and the standard option in SWMM, could contribute to overestimate ET during moisture limited conditions. Further examination of alternative options for ET modeling will be explored, specifically related to energy-based models and PET verses AET, in pursuit of model simulation and observed agreement with data.

Table 2. Sensitivity of Annual Retention and Annual Runoff Volume to SWMM Bioretention Parameters Adjusted ±10% and ±50%

	-50%		-10%		10%		50%	
Parameter	Annual Retention	Runoff Volume	Annual Retention	Runoff Volume	Annual Retention	Runoff Volume	Annual Retention	Runoff Volume
ET coefficient	-0.343	0.369	-0.277	0.292	0.229	-0.247	0.187	-0.202
Surface slope	0	0	0	0	0	0	0	0
Soil porosity	-0.0004	0.0004	0	0	0	0	0	0
Soil field capacity	-	-	-1.045	1.127	0.936	-1.010	0.667	-0.720
Soil wilting point	0.414	-0.447	0.471	-0.508	-0.508	0.547	-0.583	0.629
Soil conductivity	0	0	0	0	0	0	0	0
Conductivity slope	0	0	0	0	0	0	0	0
Suction head	0	0	0	0	0	0	0	0
Storage void ratio	0.003	-0.004	0.005	-0.005	0	0	0	0
Drain flow coefficient	0.001	-0.002	0	0	0	0	0	0
Drain flow exponent	0.001	-0.002	0	0	0	0	0	0

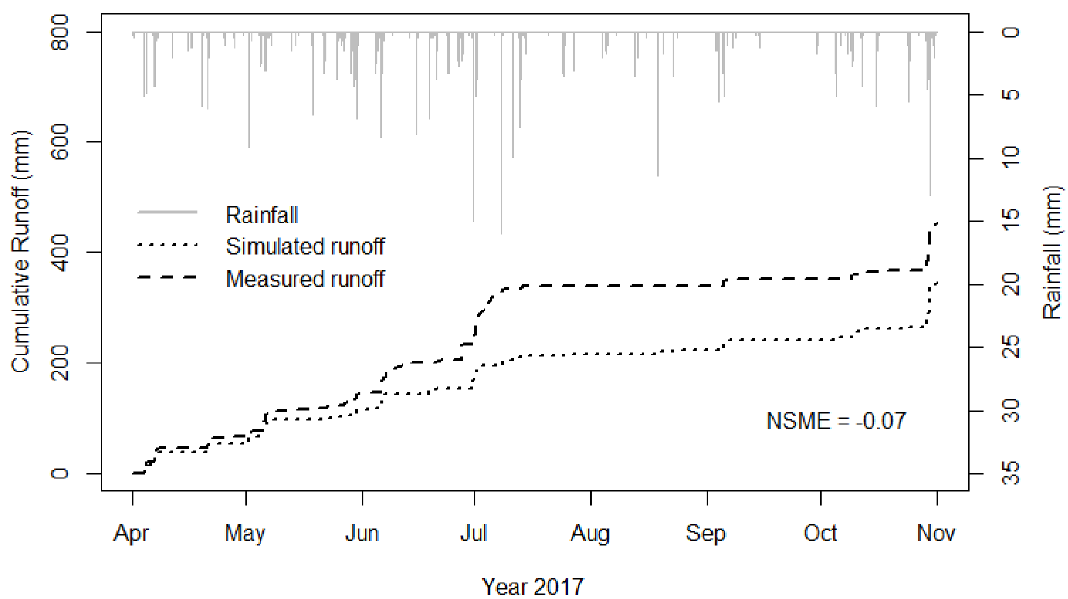

Figure 1. Uncalibrated long-term simulation. NSME calculated from hourly runoff. The rainfall is given in mm for each 1 hr timestep. The runoff is given as cumulative depth in mm.

CONCLUSIONS

The initial comparison of the results obtained from the OnCenter green roof and the SWMM bioretention module needs further investigation before concluding that the model can represent the hydrology of a green roof. The concepts of accurate PET verses AET and antecedent dry weather period are important for green roof model representation. This study is merely a first step in validating SWMM as an accurate model for a green roof in Syracuse, NY.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. DGE-1449617 and Grant No. SBE-1444755. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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